

Water delivery in the Early Solar System

Rudolf Dvorak*, Siegfried Eggl*, Áron Süli*,[†], Zsolt Sándor*, Mattia Galiazzo* and Elke Pilat-Lohinger*

**Universitätssternwarte Wien, Türkenschanzstr. 17, 1180, Wien, Austria*

[†]Department of Astronomy, Eötvös Loránd University, Pázmány Péter sétány 1/A, 1117 Budapest

Abstract. As part of the national scientific network ‘Pathways to Habitable Worlds’ the delivery of water onto terrestrial planets is a key question since water is essential for the development of life as we know it. After summarizing the state of the art we show some first results of the transport of water in the early Solar System for scattered main belt objects. Hereby we investigate the questions whether planetesimals and planetesimal fragments which have gained considerable inclination due to the strong dynamical interactions in the main belt region around 2 AU can be efficient water transporting vessels. The Hungaria asteroid group is the best example that such scenarios are realistic. Assuming that the gas giants and the terrestrial planets are already formed, we monitor the collisions of scattered small bodies containing water (in the order of a few percent) with the terrestrial planets. Thus we are able to give a first estimate concerning the respective contribution of such bodies to the actual water content in the crust of the Earth.

Keywords: Early-Solar-System, Water-Transport, Hungaria-asteroids

PACS: 96.12.Bc, 96.30.Ys

INTRODUCTION

The presence of liquid water on the surface of a terrestrial planet is a basic requirement for habitability in planetary systems. The questions one needs to answer in this connection are

- When the terrestrial planets formed how much was their content of water?
- Why don’t we find water in the same quantities on the other terrestrial planets?
- What happened to the water when a mars-sized object hit the Earth and the Moon formed?
- What happened during the Late Heavy Bombardement (LHB)
- Where from came water after the LHB?
- What is the role of the comets from the Oort Cloud?

A main problem in this context is to find out where the water came from in the early stages on the one hand; on the other hand, when water was lost during special phases in later stages one needs to explain how it was replenished on the surface. At the end one should explain also how it could stay liquid on a terrestrial planet in the habitable zone for times up to billions of years. A central question in this respect is the collisional behaviour of small bodies regarding their content of water; it has to be modelled with specially designed effective programs like the well known SPH (Smooth Particle Hydrodynamics) codes.

The possible water loss of terrestrial like planets in our Solar System (SS) and in Extrasolar Planetary system (EPS) in general should be set in context with geophysical processes like the stop of outgassing due to rapid mantle and core cooling or lack of atmospheric protection by a planetary magnetosphere

- the stellar radiative environment of young active stars (SS and EPS)
- collisions of protoplanetary objects in general (SS and EPS),
- the Late Heavy Bombardement (SS)
- the formation of the Moon (SS)

After the early stage the transport mechanisms in our SS from the main belt and also the Edgeworth-Kuiper-Belt can adequately be computed taking into account the important role of all sorts of resonances: mean motion resonances, secular resonances and three body resonances. The water delivery of the comets from the Oort cloud can be investigated statistically although it can only account for a fraction of the water on Earth regarding their different D/H ratio. Comets may have been brought into the inner SS by orbital changes due to passing stars, interstellar clouds and galactic tides leading to comet showers. Although the water transport is the central question it is of fundamental interest to investigate how organic (carbon-containing) material could be delivered which then lead or may have lead to the development of life on Earth-like planets in habitable zones.

Different scenaria will have formed very different architectures of the planets in an extra solar planetary system compared to our own system. The observed, close-in, Jupiter like planets, which evolved into such orbits via migration processes, make it difficult to explain the continuous existence of terrestrial planets on stable orbits within the habitable zone. Together with theoretical investigations on habitable planets, results from the existing satellite missions (CoRoT, KEPLER and Herschel) as well as future ones (Plato, James Webb, Gaia) combined with the progress in Earth-bound observations (Alma, ESO) will help to clarify the origin and presence of water (and organic materials) as a basis for life.

STATE OF THE ART

From many articles concerning the formation of terrestrial planets and their content of water (e.g. [16, 22, 19, 2, 23]) we can draw a coherent picture of those phases of planet-formation where the debris disk and a giant planet were already present. Following current models, most of a planet's water-content can be regarded as being produced by collisions between the growing protoplanet and Moon to Mars-sized planetesimals originating from the asteroid belt. According to [15] and also [22] the accretion of planetary embryos from distant regions (outside the snowline) by terrestrial planets could have happened also without the presence of a Jupiter-sized object. Other studies claim that the early Earth as well as the terrestrial planets were dry, just as the asteroids in the region of their formation, because only in the cold outer part of the early SS gas and water were present in big quantities ([26]). But in these phases collision events ([7, 8]) as well as the EUV radiation from the early star could have reduced the water content

in these regions (e.g. [5, 6, 13]). At any rate during a later stage water was brought onto the surfaces of the terrestrial planets and, whereas Venus and Mars could not keep their water on the surface, the Earth's magnetosphere anticipated water loss (e.g. [13]). Many scenarios try to explain the water transport onto Earth; the most plausible seems to be that the C-asteroids from the outer main belt of asteroids, main belt comets ([3]) and small bodies from outer regions of the SS up to the scattered disk, consisting in big parts of frozen water contributed to the water content on Earth.

Given the discovery of water and a subsurface ice reservoir on the asteroid 24 Themis ([4]), and comet-like activity of several small asteroids it is clear that water is in fact abundant in many solar system bodies and may even lie well hidden inside a crust. Collision probabilities, impact velocities and size distributions depend crucially on the orbits of the colliding objects as well as the perturbations of the planets on their motion respectively. Regarding these topics, namely

- formation and early development of Earth-like planets with respect to their water content,
- the possible loss of water through collisions with other celestial bodies (e.g. the impact of a Mars-like body onto the Earth with subsequent formation of the Moon, ([20], [25]) and
- late water transport,

cannot be modelled by pure gravitational N-body simulations, but with sophisticated codes including accretion, the role of the disks, the collisional growth etc.([10]). Numerous simulations concerning the formation of planets in the early Solar System have been performed where the early formation of a gas giant (Jupiter) is assumed. Hereby the giant planets are playing a key role; they formed when still there was a considerable amount of helium and hydrogen present in the early Solar nebula. Later accretion of terrestrial planets is closely connected to the perturbations due to these planets on planetesimals within the inner part of the disk ([22], [2]). The process of accretion of embryos by terrestrial planets may be possible for different giant planet configurations, and even without gas giants present in the system (e.g. [15] and [22]). Although most of the discovered EPS host at least one big planet – due to a biased sample because of the constraints in our observations – this may not be the rule for the formation of planetary systems in general (e.g. CoRoT-7b,c¹).

A crucial factor for water-delivery scenarios onto terrestrial planets is the so-called 'snowline' which is due to the outward diffusion of gas charged with vapour that condenses on existing particles during the period when its temperature changes. This change acts on the accumulation of particles that originate from further radial distances and have a faster inward migration because of their small sizes. As a consequence, water can be present as water ice bound in icy planetary embryos in the outer parts (respectively beyond the snowline) of the protoplanetary disc. Accretion of water from these bodies is a stochastic process, therefore planets may have different water content due to their

¹ CoRoT-7 is a planetary system (consisting of at least two planets) which was discovered by the space mission CoRoT (details in [12])

different histories ([19]). In this article it is also claimed that such contributions to water on terrestrial planets may be minor because of the perturbations of Jupiter. There exist quantitative estimates for the impact erosion of atmospheres and condensed oceans of planets during the LHB ([7]). But also the delivery of prebiotic organic matter (C, H, O, N and P) together with water by main belt comets and also comets from the Oort Cloud([21]) has been established via hydrodynamic simulations. According to recent results of computations by [1] some small amount of amino acids could even survive low impact velocities as subsurface habitats.

TRANSPORT OF WATER TO THE TERRESTRIAL PLANETS FROM THE HUNGARIA MAIN BELT REGION

One expects that the main source for water delivery to the Earth are asteroids in the main belt between Mars and Jupiter (as well as comets from the Oort cloud). A water gradient in the protoplanetary disk such that at 1 AU bodies were dry, whereas bodies at 2.5 AU contain 5 percent of water is the usual assumption. It is well known ([18]) that asteroid groups in the main belt with high inclination to the ecliptic plane can evolve to become Mars crossers. Such configurations seem promising candidates, if one was to look for possible mechanisms that can uphold a constant supply of material into the inner Solar System.

In our preliminary approach we took a sample of fictitious small bodies in the region where now the Hungaria family of asteroids is located. This family is believed to originate from a violent dynamical event ([18], [27]) about 0.5 Gyrs ago that caused an injection of the Hungaria predecessors into orbits with an inclination of about 20 degrees. Another interesting point is the proximity of these asteroids to the 4:1 mean motion resonance with Jupiter as well as several secular resonances as their semimajor axes are mostly between 1.8 and 2 AU). Nowadays the Hungaria group consists of more than 8000 known members with the largest objects with sizes up to 12 km. The membership of asteroids within this group to one or more families is still in debate ([18]). However, for our purposes, the existence of such bodies will be taken as a reasonable argument, that during dynamically more violent times in the later stages of the Solar System's formation, planetesimals could have been proliferated to this region of the main belt.

We have undertaken numerical simulations up to 40 million years, in order to investigate the number of possible close encounters respectively impacts of our test population with the terrestrial planets in the inner Solar System. As a dynamical model we chose to include the Venus-Earth-Mars-Jupiter-Saturn system as it is now, with exception that we did not consider the moon explicitly.

Using results by [11] 300 planetesimals were distributed in a phase space region of the Hungaria group which has been shown to lead to an increased number of close encounters. Another 648 were placed in the groups enclosing resonances. The goal was to see how quickly the respective populations become so-called Near-Earth-Asteroids, where every now and then one might have close encounters respectively impacts on the Earth (and also Mars and Venus). The four different chosen regions, where the initial

conditions for the four different samples were chosen, are given below:

- **S1**: 300 Hungarias clones with three different semimajor axes $a = 1.90792307, 1.91027822, 1.90508465$ AU and equally distributed eccentricities in the range $0.18 < e < 0.19$ and inclinations in the range of $17^\circ < i < 27^\circ$.
- **S2**: 216 clones close to the ν_{16} secular resonance² equally distributed with slightly larger semimajor axes than the Hungarias $1.9 < a < 2.1$ AU and the eccentricities and inclinations like in **S1**.
- **S3**: 216 clones close to the ν_5 secular resonance³ equally distributed with slightly smaller semimajor axes than the Hungarias $1.8 < a < 1.9$ AU and the eccentricities and inclinations like in **S1**.
- **S4**: 216 clones in the region of the ν_5 secular resonance with semimajor axes $1.85 < a < 1.95$ AU, the eccentricities like in the range of **S1** but with significantly larger inclinations $27^\circ < i < 35^\circ$.

In Fig.1 we depict the region of Hungaria family in an plot $\sin(i)$ versus the semimajor axes. Note that the bodies in samples **S1**, **S2** and **S3** have the same inclinations but their initial conditions are shifted to larger respectively smaller semimajor axes. The initial orbital elements for the fictitious bodies of **S4** are distributed in semimajor axes $1.85 < a < 1.95$ and have large initial inclinations (around 30°). of the figure).

Close Encounters with the Planets

The results for the four different planetesimal samples are summarized in the following graphs 2-5. We note that during our integrations the mutual perturbations between planetesimals was neglected and only close encounters with the planets were reported.

Depending on the close encounters we could extrapolate collision timescales which are crucial for estimates for a possible water transport onto the terrestrial planets; we estimated the water content to be three percent of the small bodies' masses.

Fig.2 shows the number of close encounters within the so-called Hill's sphere⁴. We note that for Venus the results do not agree with other studies with respect to the frequency of close encounters (e.g.[11], [9]). This is because of the relatively short integration time in our investigations. The transport of the asteroids from the Hungaria region to the inner regions of the planetary system takes longer (about several tenth of million years) than for Mars and the Earth. In Fig.3 we compare the closest encounters during the integrations for the four samples for all planets. One can see that counted in planetary radii only one real collision occurred and that is one with Jupiter. Although no collisions are reported for the terrestrial planets we can extrapolate these results of the

² where the secular nodal motion of the massless body equals the nodal motion of Saturn

³ where the secular perihelion motion of the massless body equals the perihelion motion of Jupiter

⁴ This sphere around a planet is defined as $r_H = (\frac{\mu}{3})^{\frac{1}{3}}$ where μ is the mass of the planet in Solar masses. It can be regarded as a sphere of influence where inside the gravitation of the planet is larger than the one of the Sun

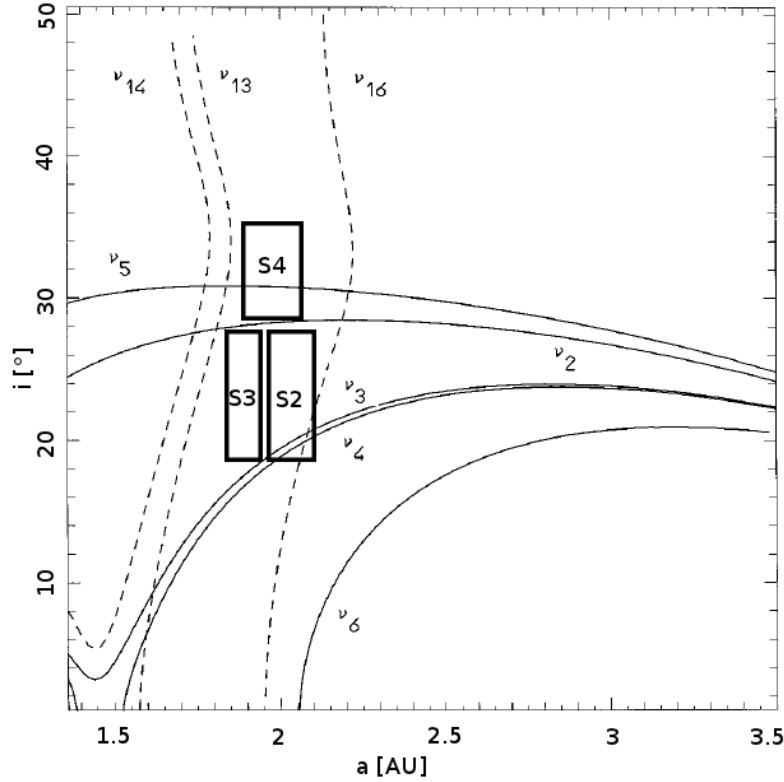


FIGURE 1. The Hungaria asteroid region in a inclination versus semimajor axes diagramm. The locations of the initial conditions of the samples **S2**, **S3** and **S4** are shown in the rectangular boxes. The initial conditions for the sample **S1**, just inside the Hungaria region, are between **S2** and **S3**. The dashed lines indicate the secular resonances involving the longitudes, the solid lines involving the perihelion longitudes between a small body and a planet. The numbers '2' - '6' stand for the planets Venus to Saturn. (after [17]).

frequency of the close encounters and find (see next chapter) an estimation of the time interval of a single Hungaria clone for an encounter. It is also visible from the graph that the (biased, see former remark about the integration time) tendency for collisions is getting larger from Venus to Jupiter; this reflects the results shown in Fig.2 where one can see the increasing number of close encounters from Venus to Jupiter. The larger values for the closest distances to Saturn in planetary radii reflects also the smaller number of encounters to this planet.

The Impacts

We need to say that in all our samples 'real' collisions were very rare! We used the results of the many encounters to the planets to derive from there a value for possible impacts (see Figs. 4 to 6). Binned values of the encounters were plotted versus the number of such events. A logarithmic least square fit provided us with the desired value

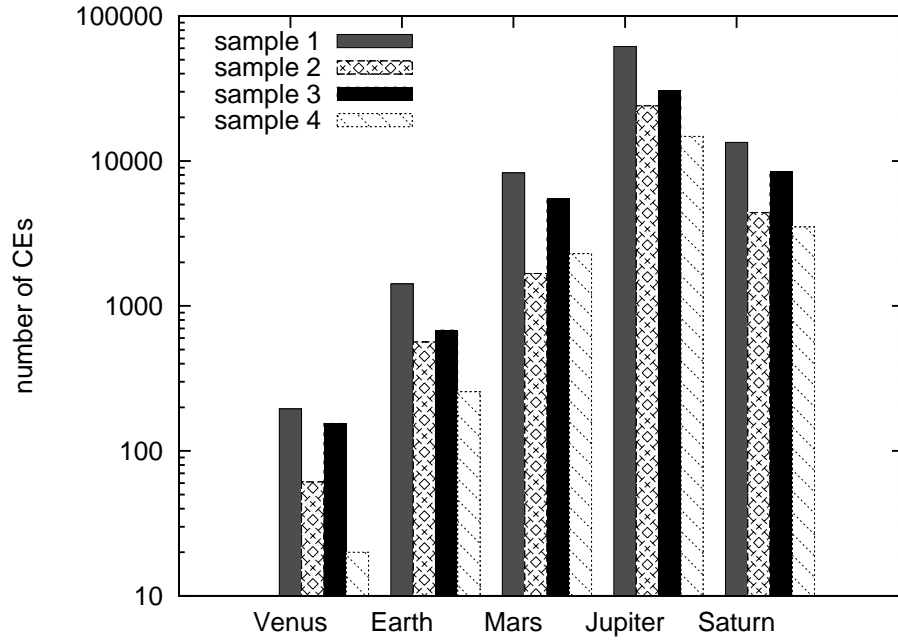


FIGURE 2. Logarithmic plot of the number of close encounters of the fictitious objects with the planets within its Hill's sphere (for more see in the text) for all the planets involved. We separate the results for the four different samples

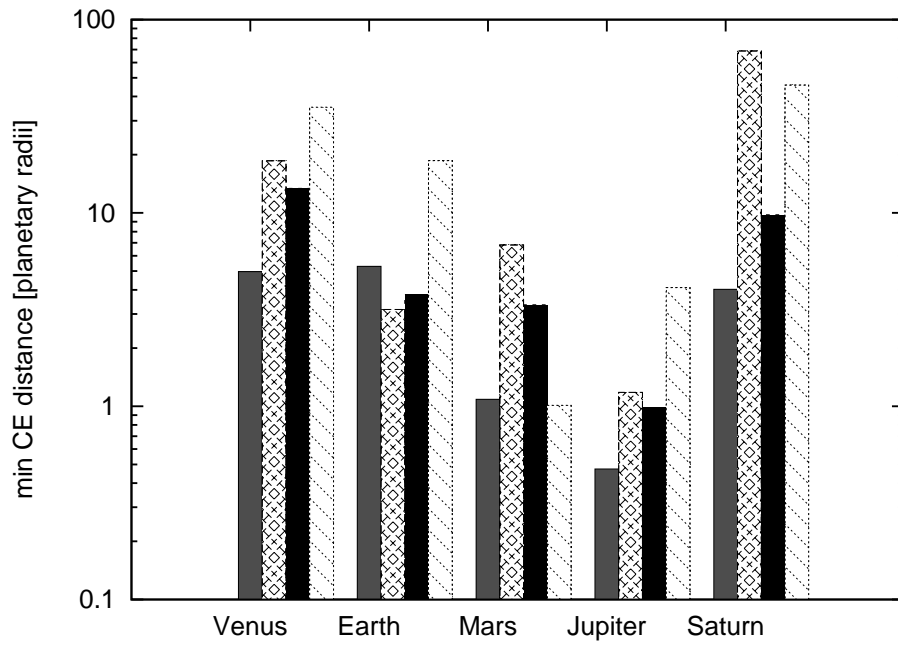


FIGURE 3. Logarithmic plot of the closest encounters to the planets in units of the radii of the planets. Detailed description in the text

TABLE 1. Impact times for the samples **S1** -**S4** (columns 3-6) onto the terrestrial planets within 1 Gyr

Planet	Radius[AU ⁻⁵]	S1	S2	S3	S4
Mars	2.25939	800.69	819.275	258.348	10.6991
Earth	4.25875	442.778	12.3894	30.3799	4.29435
Venus	4.04484	1.49954	71.7986	20.3137	0.655851

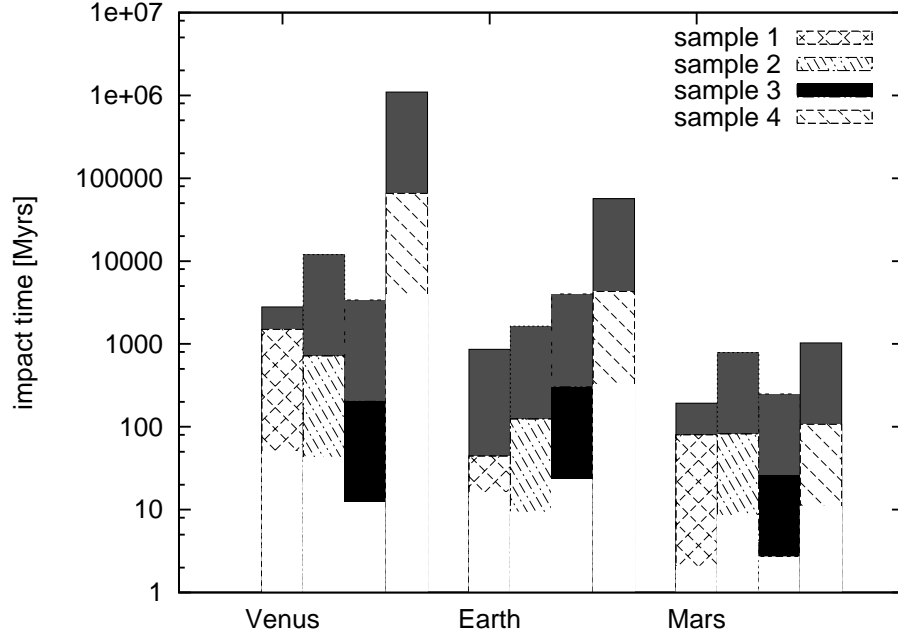


FIGURE 4. Impact time scales for Hungaria like planetesimals in the samples **S1** to **S4** on the terrestrial planets. For detail see text.

for the probability of collisions. We do not show this fit for Venus because the results are biased because of the small number of events.

It is evident that Mars – as closest to the Hungarias – suffers from impacts first of all, whereas Venus globally is the planet with the least such events (due to the relatively short time scales of integrations). Most impacts of the fictitious objects occurred in **S1**, which is a somewhat surprising fact, because shifting versus the secular resonances (**S2** and **S3**) should cause more perturbations on a body located there. Totally insignificant for the transport of small bodies to the inner system seems to be the group **S4**, which is probably due to the large inclinations we have chosen for the initial conditions.

In Fig.4 we plotted the mean values of the impact time scales which are the intersecting lines between the patterned and full bar segments. The mean values plus one standard deviation are denoted by the top of the bars, mean values minus one standard deviation by the bottom end of the patterned region. The large errors (especially for Venus and for all planets in **S4**) are caused by the poor statistics due to the choice of the integration time respectively the initial conditions.

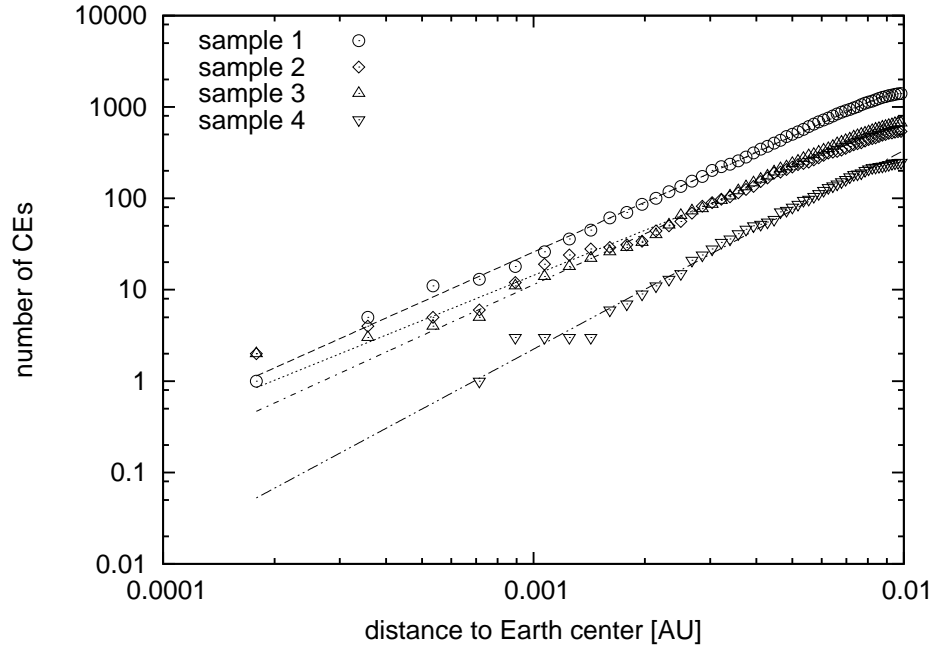


FIGURE 5. Logarithmic least square fit for the encounters with Earth using the results of samples **S1** to **S4**

In addition to the former results we have undertaken numerical experiments with a fictitious planetary system consisting of more massive terrestrial bodies comparable to a recent study by [24]. In our new study of the sample **S1**, also for 300 clones representing small bodies, we have taken five times large masses⁵ for these planets; we expected many more impacts because of the higher gravitational perturbations. In fact in contrary to the former results for the 'real' SS where only 1 'real' collision (namely with Jupiter) was reported in this investigation the results are the following ones:

- 5 with Venus at 8.9, 8.58, 19.1, 34.7 and 38.6 myrs
- 3 with Earth at 33.9, 43.13 and 46 myr
- 2 with Mars 18.1 37.8 myr
- 1 with Jupiter at 37.7 myr

These results agree much better with the ones we mentioned above, namely that Venus is suffering the most of collisions. We can explain this – expected result – that the time scales of transport of the 'planetesimals' to the inner SS are much faster in the case with $\kappa = 5$.

⁵ like in the former mentioned paper we define a multiplication factor κ for the terrestrial planets

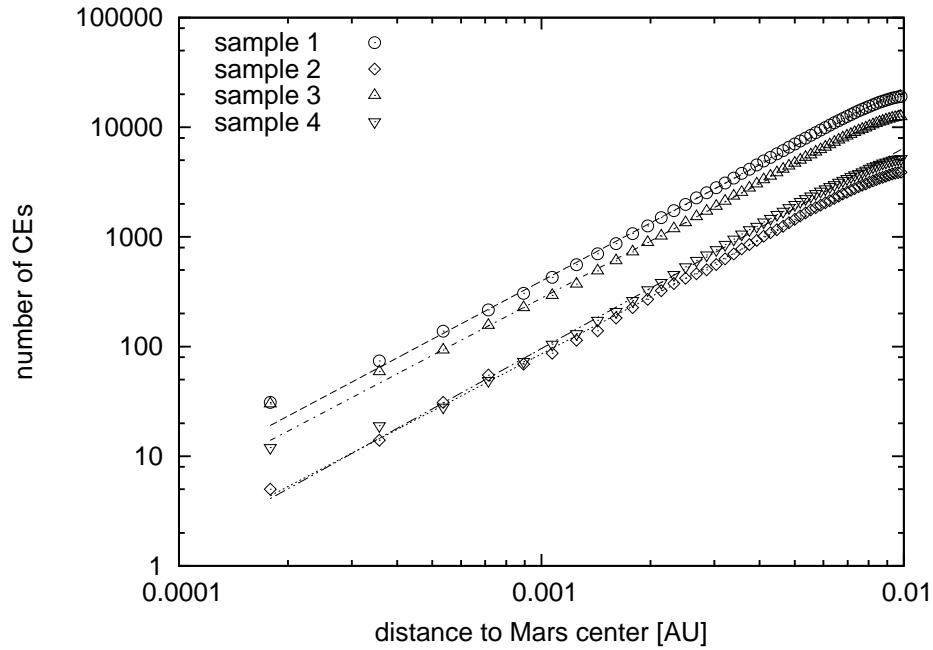


FIGURE 6. Logarithmic least square fit for the encounters with Mars using the results of samples **S1** to **S4**

CONCLUSIONS: WATER FROM HUNGARIA LIKE PLANETESIMALS?

The values from the former Tab.1 can now be used to estimate not only the how many bodies from this region may hit the Earth, it can also be used to estimate – in principle – how much water was transported from this region in the SS to our planet. Because of the very small number of impacts (see Tab.1) the contribution to the water in the crust of the Earth (estimated to be several $10^{-4}M_{Earth}$) is for sure insignificant!

Another result is of interest in this context: by far Mars suffers from most of such impacts and thus received a lot of more water even than Earth. But where is the water now? New results show that man structures on the surface of Mars are due to floating water. During the development of the Solar System this planet lost most of its water because the thin atmosphere, the much lower gravitation field and the absence of a protecting magnetosphere ([14])

For the water on Earth we can summarize that the phase space region around the Hungaria asteroid group is capable of injecting planetesimals into the inner Solar System but the total number is in fact far to low. The timescales necessary for a considerable number of impacts are too large to constitute an efficient water transport mechanism and to contribute to our actual water on our planet and thus this region can be excluded as source for water delivery to the Earth.

This preliminary study can be understood as a first step of investigation of the whole phase space between Mars and Jupiter with respect to the transport to terrestrial planet crossing regions (region of Near Earth Asteroids) and thus to possible collisions of

small bodies with different water content on these planets, especially on the Earth.

ACKNOWLEDGMENTS

The authors R.D., A.S., Z.S. and E.P.L. need to thank the NFN (Nationales Forschungsnetzwerk) 'Pathways to Habitable worlds' from the Fonds zur Förderung der Wissenschaft Nr. S 11603-N16 and S-11608-N16, S. Eggl would like to acknowledge the support of University of Vienna's Forschungsstipendium 2012; M.Galiazzo has to thank the Doctoral School at the University of Vienna 'From Asteroids to Impact Craters'

REFERENCES

1. Abramov, O., Mojzsis, S. J., *Nature*, **459**, pp. 419–422 (2009)
2. Alibert, Y., Mordasini, C., Benz, W. and Naef, D., "Testing planet formation models against observations," in *EAS Publications Series*, edited by K. Goździewski et al., pp. 209–225 (2010).
3. Bertini, I., *Planetary and Space Science*, **59**, pp. 365–377 (2011).
4. Campins, H., Hargrove, K., Pinilla-Alonso, N., Howell, E. S., Kelley, M. S., Licandro, J., Mothé-Diniz, T., Fernández, Y. and Ziffer, J., *Nature*, **464**, pp. 1320–1321 (2010).
5. Chassefière, E., *Journal of Geophysical Research*, **101**, pp. 26039–26056, (1996).
6. Chassefière, E., *Icarus*, **124**, pp. 537–552, (1996).
7. Chyba, C. F. *Nature*, **348**, pp. 113–114 (1990a)
8. Chyba, C. F., *Nature*, **343**, pp. 129–133 (1990b)
9. Dvorak, R. and Pilat-Lohinger, E., *Planetary and Space Science*, **47**, pp. 665–677 (1999)
10. Eggl, S. and Dvorak, R., *Lecture Notes in Physics*, **790**, pp. 431–480 (2010).
11. Galiazzo, M., Bazso, A. and Dvorak, R. (in preparation)
12. Hatzes, A. P., Dvorak, R., Wuchterl, G., Guterman, P., Hartmann, M., Fridlund, M., Gandolfi, D., Guenther, E. and Pätzold, M., *Astronomy and Astrophysics*, **520**, (2010),
13. Lammer, H., Eybl, V., Kislyakova, K. G., Weingrill, J., Holmström, M., Khodachenko, M. L., Kulikov, Y. N., Reiners, A., Leitzinger, M., Odert, P., Xiang Grüss, M., Dorner, B., Güdel, M. and Hanslmeier, A., *Astrophysics and Space Science*, **69**, (2011).
14. Lammer H. et al. (submitted to Space Science Library)
15. Levison, H. F. and Agnor, C., *Astronomical Journal*, **125**, pp. 2692–2713 (2003).
16. Lunine, J. I., Chambers, J., Morbidelli, A. and Leshin, L. A., *Icarus*, **165**, pp. 1–8 (2003).
17. Michel, P. and Froeschlé, Ch. *Icarus*, **128**, pp. 230–240 (1997)
18. Milani, A., Knežević, Z., Novaković, B. and Cellino, A., *Icarus*, **207**, pp. 769–794 (2010)
19. Morbidelli, A., Chambers, J., Lunine, J. I., Petit, J. M., Robert, F., Valsecchi, G. B. and Cyr, K. E., *Meteoritics and Planetary Science*, **35**, pp. 1309–1320 (2000).
20. Pahlevan, K. and Stevenson, D. J., *Earth and Planetary Science Letters*, **262**, pp. 438, (2007).
21. Pierazzo, E. and Chyba, C.F., *Advances in Astrobiology and Biogeophysics*, pp. 137, (2006)
22. Raymond, S. N., Quinn, T. and Lunine, J. I., *Icarus*, **168**, pp. 1–17 (2004).
23. Raymond, S. N., Armitage, P. J., Moro-Martin, A., Booth, M., Wyatt, M. C., Armstrong, J. C., Mandell, A. M., Selsis, F. and West, A. A. *ArXiv e-prints*, (2011).
24. Süli, Á and Dvorak, R., *Astronomische Nachrichten*, **328**, pp. 4–9 (2007)
25. Taylor, J. *American Geophysical Union, Fall Meeting 2010*, (2010).
26. Trigo-Rodríguez, J. M. and Martín-Torres, F. J., *ArXiv e-prints*, (2011).
27. Warner, B. D., Harris, A. W., Vokrouhlický, D., **204**, pp. 172–182 (2009)